Holonic Virtual Geographic Environments

Mehdi Mekni[*1]

Math, Science and Technology Department, University of Minnesota Crookston

2900 University Avenue, Crookston, MN 56716

[*1]mmekni@umn.edu

Abstract

In this paper, a novel model for the representation of geographic environnements has been proposed called *Holonic Virtual Geographic Environments*, in which the holonic approach is employed as a computational geographic methodology and holarchy as organizational principle. Our approach allows automatically building virtual geographic environments using data provided by geographic information systems and enables an explicit representation of the geographic environment for multi-Agent systems in which agents are situated and with which they interact. Taking into account geometric, topologic, and semantic characteristics of the geographic environment, we propose the use of the holonic approach to build the environment holarchy. Our holonic model has been depicted using two different environments: an urban environment and a natural environment.

Keywords

Situated Multi-Agent Systems; Geographic Information Systems; Geo-Simulation

Introduction

The importance of the environment as a *first-order abstraction* is particularly apparent for *Situated Multi-Agent Systems* (SMAS) (Weyns, Omicini, Odell, 2007) that are characterized with an explicit spatial environment called *Virtual Geographic Environment* (VGE) in which agents are situated. Indeed, such a representation must take into account the geometrical information corresponding to various geographic features. Moreover, this representation must qualify space by means of association of semantics with geographic features in order to allow spatial reasoning. *Geographic Information Systems* (GIS) provide such features but in an inefficient way when fast and automated spatial reasoning algorithms are in consideration (Mekni, 2010). In addition, modelling large scale geographic environments is a complex process (Yang., Gong, Hu, Wang, 2006).

Current approaches aim at regarding the environment as a monolithic structure which considerably reduces the capacity to handle large scale, real world environments (Rodriguez, Hilaire, Galland, Koukam, 2006). In order to build realistic SMAS, we need an explicit environment representation which efficiently organises the geographic features, accurately captures the real world complexity, and reliably models large scale geographic environments.

The *holonic* approach has been successfully applied to a wide range of applications including industrial (Fletcher, Hughes, 2006), military (McGuire, Liggins, Wojcik, Benaskeur, Brennan, 2006), environment monitoring (Mekni, 2010), to name a few. Moreover, the *holonic* approach is a suitable organizational paradigm that may be helpful for the space decomposition and organization of geographic features (Rodriguez, Hilaire, Galland, Koukam, 2006).

The term *"holon"* was originally coined by Arthur Koestler (Koestler, 1967), based on the Greek word *"holos"* for "whole" and the suffix *"–on"* that denotes *"part"*. According to Koestler, a holon , a fractal structure that is stable, coherent, consists of several holons acting as sub-structures. In this definition, a holon itself can be considered as part of a higher level architecture of holons. As an illustration in geographic context, a holonic decomposition of the geographic environment would comprise regions which in turn consist of groups of cells that can be further decomposed, and so on. Furthermore, the geographic environment may be part of a province and a country. None of these components can be understood completely without its sub-components or the super component they are part of. Several holons, having each its own identity, can exist together as components of a given system.

In this system, called a *holarchy*, holons are independent with respect to their subordinate parts and simultaneously dependent of parts of higher hierarchic levels. Thus, a holarchy denotes a hierarchical organization of holons having a recursive structure (Koestler, 1967). This structure can guarantee performance stability, predictability, flexibility, adaptability, and global optimization of hierarchical

control (Rodriguez, Hilaire, Galland, Koukam, 2006).

In this paper, a novel approach has been proposed to model *Holonic Virtual Geographic Environments* (HVGE) in which the *holonic* approach is utilized as a computational geographic methodology and the *holarchy* as an organizational principle. Our approach provides an exact representation of the geographic environment using GIS data. This representation is organised as a topological graph, enhanced with data integrating both quantitative data (like the geometry) and qualitative information (like the types of zones such as roads and buildings). This study focuses on the environment description and takes advantage of the holonic approach in order to address the following issues: 1) the way to efficiently and accurately model complex geographic spaces in order to build accurate VGE; 2) the way to structure, organize, and inform such a VGE in order to provide an easy and fast access to data describing the real world to situated agents to reason about it.

Next section presents a discussion of related works on modelling and representation of geographic environments. In Section 3, we introduce the geographic concepts used in our model. Section 4 presents our novel holonic modelling approach of large scale geographic environments. In order to demonstrate the generic aspect of the proposed model, in Section 5 two different experimental models are shown. The first refers to a geographic holonic model representing the *Montmorency* experimental forest (*St.Lawrence Region, QC, Canada)*. The second illustrates the urban holonic model of a part of Quebec city (*QC, Canada*). Section 5 concludes the paper and presents future work.

Related Work

While most works on *Multi-Agent Systems* (MAS) out emphasis on the design of autonomous agents organisations, few research works have been found addressing the environment description and representation. Farenc proposed an informed environment dedicated to urban life simulation, which is based on a hierarchical decomposition of a urban scene into environment entities providing geometrical information associated with semantic notions (Farenc, Boulic, Thalmann, 1999). This approach puts forward the importance ofthe integration of additional information in order to enrich the environment description but lacks a systematic method to decompose the geographic environment (FIG. 1).

FIG. 1 INFORMED ENVIRONMENT DEDICATED TO URBAN LIFE SIMULATION

Musse used this informed environment to animate human crowds by using a hierarchical control (Musse, 2000): a virtual human agent belongs to a group that belongs to a crowd, and an agent applies the general behaviours defined at the group level. However, very few works on the modelling of large scale geographic environments using the holonic approach have been found in the literature.

Authors in (Rodriguez, Hilaire, Galland, Koukam, 2006) proposed a geographic representation of an industrial plant for traffic analysis purposes. This study uses the holonic approach to decompose real world environment in terms of holonsand shows the contribution of such an approach in reducing the complexity of real world environments and demonstrates the capability of the holonic approach to organize various geographic features (road, exchange point, segment, link). However, there isno available information about the methodology they use to build what they call *3D virtual* world. In addition, there is limitation in these authors' claims that their approach can be used to model large scale geographic environments. First of all, the focus of their work is on traffic analysis; therefore the model only takes into account the geographic features that are involved in the traffic flow. Secondly, the surface of the industrial plant is around (2km^2) which is a relatively small area to be qualified as a large scale geographic environment. The lack of efficient models capable to represent large scale geographic environments while the geometric, topologic, and semantic characteristics of the space in consideration motivated us to propose a novel approach based on a holonic approach which allows the combination of semantic data, accurate subdivision of the space, and the offer of an environment holarchy built upon a topological graph. In the following

section, the fundamental geographic concepts involved in this work is introduced.

Geographic Data and Spatial Subdivision

GIS data are usually available in either *raster* or vector formats (Wang, 2005). The raster format subdivides the space into regular square cells, called boxes, associated with space related attributes (FIG. 2). This approach generally presents quantitative data whose precision depends on the scale of the representation. In contrast, the vector format exactly describes geographic information without constraining geometric shapes and generally associates qualitative data with each shape. Such data are usually exploited in a VGE in two ways (Gong, Hui., 1999): *approximative* and *exact* spatial subdivision methods.

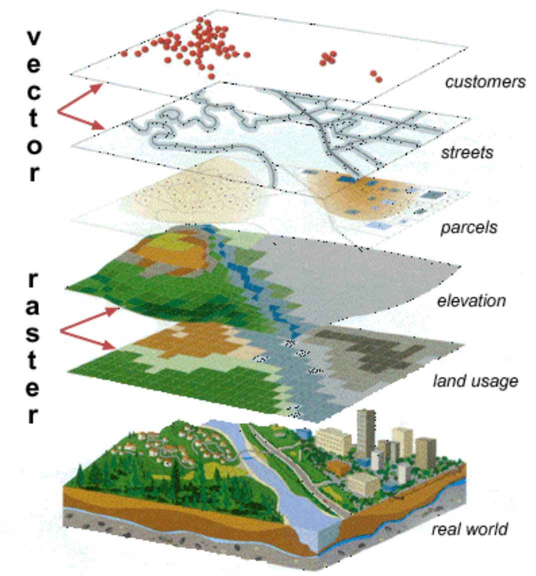


FIG. 2 GIS DATA REPRESENTATION (Goodchild, 2006)

The *approximative* subdivision can be used to merge multiple semantic data (Zhu, Gong, Lin, Li, Zhang, Wu, 2005), the locations where these data predefined by the grid cells are stored. The main drawback of this discrete method is related to a loss in location accuracy, making it difficult to accurately position any information which is not aligned with the subdivision (FIG. 3 (a)). Another drawback arises in the course of the precise representation of large environments using a grid: the number of cells tends to increase dramatically, which makes the environment exploitation very costly. The grid-based method is mainly used for animation purposes because of the fast data access it provides (Tecchia, Loscos.,Chrysanthou, 2002).

The second method, called *exact* subdivision, consists in subdividing the environment in convex cells using the vector format as an input. The convex cells can be generated by several algorithms, among which the most popular is the *Constrained Delaunay Triangulation* (CDT) (Kallmann, Bieri, Thalmann, 2003).

The CDT produces triangles while keeping the original geometry segments named constraints (FIG. 3 (b)). The primary advantage of the exact subdivision method is to preserve the input geometry, allowing foraccurately manipulation and visualization of the environment at different scales. Another advantage of this approach is that the number of produced cells only depends on the complexity of the input shapes, but not on the environment's size and scale as it is the case with the grid method. The main drawback of this approach is the difficulty to merge multiple semantic data for overlapping shapes. Moreover, this method is generally used to represent planar environments because the CDT can only handle 2D geometries. This method tends to be used for microscopic simulations where accuracy is essential.

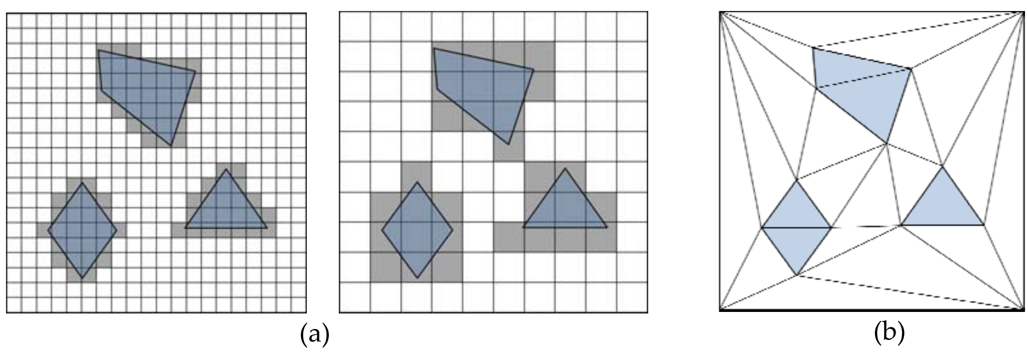


FIG. 3 EXAMPLES OF SPATIAL DECOMPOSITION TECHNIQUES: (a) APPROXIMATE SPATIAL DECOMPOSITION USING GRIDS; (b) EXACT SPATIAL DECOMPOSITION USING DELAUNEY TRIANGULATION

Two kinds of information can be stored in the description of a VGE. Quantitative data are stored as numerical values which are generally used to depict geometric properties (like a path's width of 2 meters) or statistical values (like a density of 2.5 persons per square meter). Qualitative data are introduced as identifiers which can be a reference to an external database or a word with an arbitrary semantic, called a label. Such labels can be used to qualify an area (like a road or a building) or to interpret a quantitative value (like a narrow passage or a crowded place). An advantage of interpreting quantitative data is to reduce a potentially infinite set of inputs to a discrete set of values, which is particularly useful to condense information in successive abstraction levels to be used for reasoning purposes (Mekni, 2011). The approach we propose is based on an exact representation of the environment whose precision allows more realistic applications like sensor web management (Mekni, 2010).

Generation of the Environment Holarchy

An automated approach has been put forward to generate the environment holarchy data directly from vectorial GIS data.

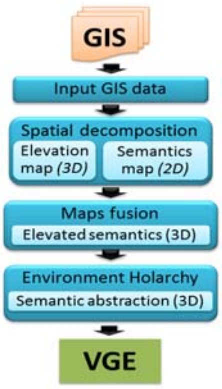


FIG. 4 THE HOLONIC IVGE GENERATION (Mekni, 2010)

This approach is based on four stages which are detailed in this section (FIG. 4): input GIS data, spatial decomposition, maps fusion, and Environment holarchy. The geographic environment can hence be thought of as a holarchy of abstracted graph in which higher level graphs contain less holons (grouped cells) and have a low discrimination potential in spatial reasoning (FIG. 5).

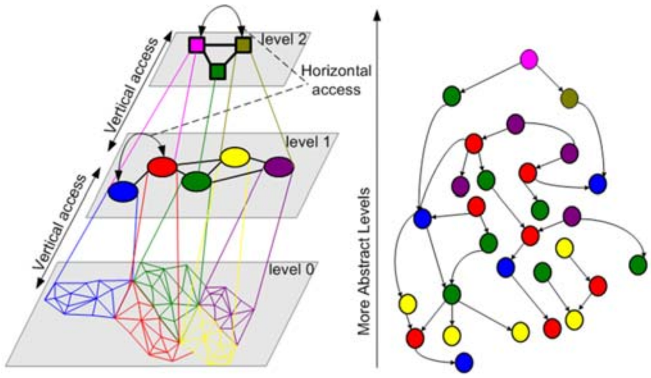


FIG. 5 THE ENVIRONMENT HOLARCHY STRUCTURE

Input GIS Data

The first step of our approach is *Input GIS* data and consists in the selection of different GIS vector data which will be used to build the VGE. The only restriction concerning these data is that they need to respect the same scale and to be equally geo-referenced. The input data can be organised in two categories. Firstly, elevation layers contain geographical marks indicating absolute terrain elevations. Secondly, semantic layers are used to qualify various features of the geographic space. As shown in FIG. 6, each layer indicates the geographic boundaries of a set of features having identical semantics, such as roads and buildings. The features' boundaries can overlap between two layers, and our model is able to merge this information.

(a) (b) (c) (d) (e)

FIG. 6 VARIOUS SEMANTIC LAYERS RELATED TO QUEBEC CITY: (a) ROAD NETWORK; (b) OLD COITY WALL; (c) GOVERNMENTAL BUILDINGS; (d) HOUSES; (e) MARINA

(a) (b) (c)

FIG. 7 (a) SPATIAL DESOMPOSITION AND (b, c) SEMANTIC MERGING AND MAP FUSION OF QUEBEC CITY.

Spatial Decomposition

The second step of our method is *Spatial Decomposition* and consists in the acquisition of an exact spatial decomposition of the input data in cells. This process is entirely automatic, using a Delaunay triangulation, and can be divided into two parts in relation to the previous phase. At first, an elevation map is computed, corresponding to the triangulation of the elevation layers. All the elevation points of the layers are injected in a 2D triangulation, and the elevation is considered as an additional datum. This process produces an environment subdivision composed of connected triangles as shown in FIG. 7(a) et FIG. 11(a). Such a subdivision provides information about coplanar areas: the elevation of any point inside the environment can be deduced thanks to the elevation of the three vertices of the corresponding triangle. Then, a merged semantics map is computed, corresponding to a Constrained Delaunay Triangulation (CDT) of the semantic layers. Indeed, each segment of a semantic layer is injected as a constraint which keeps track of the original semantic data thanks to an additional datum. Consequently, the resulting map is a CDT merging all input semantics: each constraint represents as many semantics as the number of input layers containing it. For example, FIG. 7(b) et FIG. 11(b) present the resulting CDT of the geographic features provided respectively in FIG. 6 and FIG. 10 by means of the same colours for each semantic.

Maps Fusion

The third step to obtain the VGE data is called *Maps Fusion* and consists in unification of the two maps previously obtained. This phase corresponds to the mapping of the 2D merged semantic map (FIG. 7(b) et FIG. 11(b)) on the 2.5D elevation map (FIG. 7(a) et FIG. 11(a)) in order to obtain the final 2.5D elevated merged semantics map (FIG. 7(c) et FIG. 11(c)).

At beginning, a preprocessing is carried out on the merged semantics map in order to preserve the elevation precision inside the unified map. Indeed, all the points of the elevation map are injected in the merged semantics triangulationto create new triangles. This first process can be dropped if the elevation precision is not an important issue. Then, a second process elevates the merged semantics map. The elevation of each merged semantics point P is computed by retrieving the triangle T of the elevation map whose 2D projection contains P. Once T is obtained, the elevation is simply computed by projecting P on the plane defined by T using the Z axis. When P is outside the convex hull of the elevation map, no triangle can be found and the elevation cannot be directly deduced. In this case, the average height of the points of the convex hull which are visible from P is in use.

Environment Holarchy

The fourth and last step of our model is called *Environment holarchy* built upon the obtained fused map which contains a set of cells embedding all the semantic information of the input layers, along with the elevation information. Data of this map are mapped to a topological graph, where each node corresponds to the map's triangles, and each arc to the adjacency relations between these triangles. Each node of a graph of level n+1 contains a subset of the graph of level n, composed by at least one node. In order to organize this graph-based spatial structure, a holarchy of abstracted graphs is proposed (FIG. 5).

This holarchy is fundamentally based on the following

roles: Head and Part. The head represents members of its holonic organization. Its responsibilities are limited to:

- integrate new members to its holon group, and
- to release members irrelevant to the holarchy.

The part responsibilities are basically: 1) remain member of a holarchy, and 2) seek for a holarchy to join. The environment holarchy is obtained by the application of a two phase process: 1) *grouping connex cells* to form *groups* of cells, the 2) merging of semantically coherent groups in order to form *zones*. The convex cell grouping phase (phase1) is characterised with a strict geometric constraint considering the convexity of the generated groups. During this phase, the head takes the decision to integrate or realise a member based on the following model:

$$Func_{Head}(h_i) = \left| \begin{array}{l} \text{if } \nabla(\text{Semantic}(h_i), S) \text{ Then} \\ \max\,(C(Head \cup h_i), C(Head)) \\ \qquad\qquad Else \\ \qquad\qquad C(Head) \end{array} \right.$$

$Func_{Head}(h_i)$ refers to the decision making model of the head regarding the integration of the candidate holon h_i. $\nabla(S_i, S_j)$ is a *compatibility* function between semantics S_i and S_j whose evaluation is a *boolean*. C is the convexity factor and computed as follows: $C(h_i) = {Surface(h_i)} / {Surface(CH(h_i))}$ and $0 \le C(h_i) \le 1 * CH(h_i)$ is the convex hull of the geometric form corresponding to the holon h_i, Semantic(h_i) is the semantic of the holon h_i, and *S* is the list of the *Head* semantics.

The *Head* checks if the semantic information of h_i is *compatible* with its semantic information set *S*. If the test is conclusive, the *Head* computes the convexity factor of its geometric form with and without the candidate h_i. The integration of the holon h_i must maximise the convexity factor of the *Head* (i.e. C(*Head* $\cup$ h_i) > C(*Head*). The same logic is applied for released members. The release of the holon h_j must optimise the convexity factor of the *Head* (i.e. C(*Head* \ h_j) > C(Head)). The merging of semantically coherent groups (phase 2) is characterised with a less strict geometric constraint regarding the convexity of the generated zones and a higher priority to their semantics compatibility functions ∇. Moreover, dependent on the application purposes, designers may apply this second phase grouping strategy several times while progressively increasing the priority of the semantic grouping rules and decreasing the geometric constraint. An example of semantic grouping rules may correspond to the *crossable* relationship between groups. However, designers may freely adopt application-dependent semantic merging rules. For example, a group of cells qualified as *road* can be grouped with a group of cells qualified as *highway* in order to create a zone which enables situated agents representing cars to navigate in the VGE.

In the same way, a group of cells qualified as *sidewalk* can be grouped with a group of cells qualified as *crosswalk* in order to allow situated agents representing pedestrians that can cross roads and thus navigating in the VGE. The extraction of these new graphs which form the environment holarchy drastically reduces the number of nodes at each abstraction. For example, in a path planning context, the more an abstract node contains potential sub paths, the less its choice impact the path finding process.

Geometric Abstraction

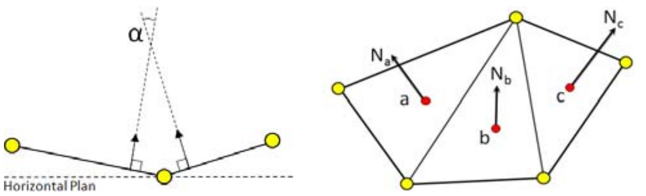
The spatial decomposition subdivides the environment into convex cells. Such cells encapsulate various quantitative geometric data suitable for accurate computations. Since geographic environments are seldom flat, it is important to consider the terrain's elevation, which is a relevant information characterized with geographic environments. Moreover, while elevation data are stored in a quantitative way applied to exact calculations, spatial reasoning often needs to manipulate qualitative information. Indeed, when a slope is in consideration, it is obviously simpler and faster to be qualified using an attribute such as *light* and *steep* rather than using numerical values. However, when dealing with large scale geographic environments, handling the terrain's elevation, including its light variations, it may be a complex task. To this end, an abstraction process is proposed in which geometric data are in use to extract the average terrain's elevation information from spatial areas. The objectives of this *Geometric Abstraction* include three aspects (Mekni, 2011)the first of whichis to reduce the amount of data used to describe the

environmentthento detect anomalies, deviations, and aberrations in elevation dataand the last is about the geometric abstraction enhancing the environmental description by integrating qualitative information characterising the terrain's elevations.

Geometric Abstraction Algorithm

The geometric abstraction process gathers cells in groups according to a geometric criterion: the coplanarity of connex cells are selected in order to obtain uniform elevation areas. The algorithm takes advantage of the holarchy structure obtained due to the HVGE extraction process.

The aim of this algorithm is to group *cells* which verify a geometric criterion in order to build *groups* of cells. A *cell* corresponding to a node which represents a triangle generated by the CDT spatial decomposition technique in the topological graph. ischaracterized with its boundaries, its neighbouring cells, its surface as well as its normal vector which is a vector perpendicular to its plan FIG. 8 (a)).



(a) (b)

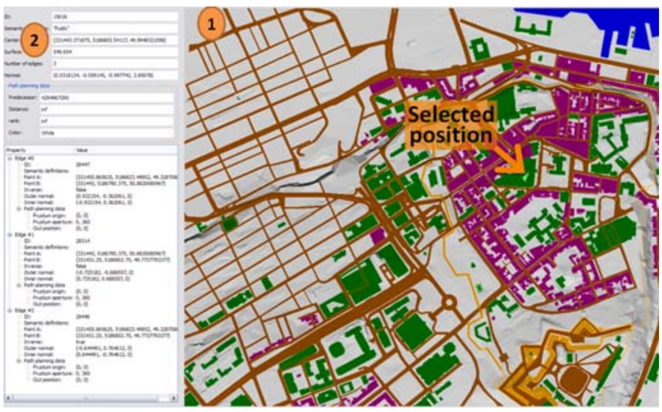
FIG. 8 (a) ILLUSTRATION OF TWO COPLANAR CELLS, (b) UNIT NORMAL VECTORS

A *group* is a container of adjacent cells. The grouping strategy of this algorithm is based on a coplanarity criterion assessed by compution of the difference between the *normal vectors* of two neighbouring cells or groups of cells (FIG. 8). Since a group is basically composed of adjacent cells, it is obvious to characterise a group by its boundaries, its neighbouring groups, its surface, as well as its normal vector. However, the normal vector of a group must rely on an interpretation of the normal vectors of its composing cells. In order to compute the normal vector of a group, we adopt the area-weight normal vector (Chen & Wu, 2005) which takes into account the unit normal vectors of the inclusive cells as well as their respective surfaces. The area-weight normal vector of a group $\vec{NG}$ is computed using:

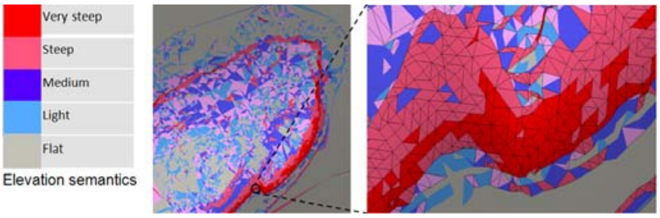
$$\vec{NG} = \sum_{c \in G} (S_c . \vec{N_c}) / \sum_{c \in G} S_c \quad (1)$$

Where S_c denotes the surface of a cell c and $\vec{N_c}$ be its unit normal vector. Hence, owing to the area-weight normal vector, it is possible to compute a normal vector for a group based on the characteristics of the inclusive cells. The geometric abstraction algorithm uses two input parameters: 1) a set of *starting cells* which act as access points to the graph structure, and 2) a *gradient* parameter which corresponds to the maximal allowed difference between cells' inclinations. Indeed, two adjacent cells are considered coplanar and hence grouped, when the angle between their normal vectors (α in FIG. 8 (a)) is lesser than *gradient*.

The analysis of the resulting groups helps identifying anomalies in elevation data. Such anomalies need to be fixed in order to build a realistic virtual geographic environment. Furthermore, the average terrain's elevation which characterises each group is a quantitative data described using area-weighted normal vectors. Such quantitative data are too precise to be used by qualitative spatial reasoning.% as in the above-mentioned slope example. For example, when a slope in a landscape is considered, it is simpler and faster to be qualified using a simple attribute that takes the values *light* and *steep* rather than be expressed using the angle value with respect to the horizontal plane. Hence, a qualification process % which aims to associate semantics with quantitative intervals of values characterizing groups' terrain inclinations would greatly simplify spatial reasoning mechanisms. In addition, in order to fix anomalies in elevation data and to qualify the groups' terrain inclinations, a technique to improve the geometric abstraction of the VGE is applied. The geometric abstraction allows improvement of HVGE by filtering the elevation anomalies, qualifying the terrain's elevation using semantics and integrating such semantics in the description of the geographic environment.



(a)



(b)

FIG. 9 (a) 2D MAP VISUA:LIZATION OF THE HVGE. (1) UNIFIED MAP, (2) INFORMATION ABOUT THE SELECTED POSITION. (b) RESULTS OF THE GEOMEYRIC ABSTRACTION PROCESS

A detailed description of the geometric abstraction algorithm as well as GIS data filtering and elevation qualification processes are provided in (Mekni, 2011). The geometric abstraction built using a graph traversal algorithm groups cells based on their area-weighted normal vectors (FIG. 9 (b)). The objectives of the geometric abstraction include three aspectsthe first of which is to qualify the terrain's elevation of geographic environments in order to simplify spatial reasoning mechanisms, and second of which is to identify and fix elevation anomalies in initial GIS dataas well as to enriche the description of geographic environments by integrating elevation semantics.

Results

In order to highlight the generic aspect of our holonic approach to model large scale geographic environments, two different kinds of environments have been selected, one of which is a urban environment corresponding to a part of Quebec city (*QC, Canada*) which covers an area of 35 km². This urban environment is extracted from various GIS data sources FIG. 6.

The first level of the environment holarchy approximately contains 125,000 triangles (cells). While the second level contains around 77 000 groups of cells, and finally the third level encompasses 12 000 zones. the other one is a geographic environment representing the *Montmorency* experimental forest (*St.Lawrence Region, Quebec, Canada*) and covering an area of 47 km². This natural environment is extracted from various GIS data sources (FIG. 10).

The first level of the environment holarchy approximately contains 178 000 triangles (cells). While the second level contains around 92 000 groups of cells, and finally the third level encompasses 27 000 zones. The performances of the environment extraction process are very good, capabel to process the urban environment holarchy in less than 3.2 seconds and the natural environment holarchy in less than 3.9 seconds on a standard computer (Intel Core 2 Duo processor 2.13 Ghz, 1G RAM).

The proposed environment extraction method is used in an HVGE application, which is currently operated in a crowd simulation project. This application is able to sustain the advantages of standard GIS visualisations (FIG. 12): the semantic merging of the grids, along with the accuracy of the vector layers. Thanks to the automatic extraction method that we propose, our system handles the HVGE construction directly from a specified set of vectorial GIS files. Likewise, due to the proposed automatic extraction method, this application deals with the HVGE construction directly from a specified set of vectorial GIS files.

Two visualisation modes are available for the computed data, in the first of which, a 3D view (as shown in FIG. 9) allows freely operating in the virtual environment. An optional mode is put forward for this view where the camera is constrained at a given height above the ground, allowing following the elevation variations when navigating.

(a) (b) (c) (d) (e)

FIG. 10 DIFFERENT SEMANTIC LAYERS RELATED TO MONTMORENCY EXPERIMENTAL FOREST: (a) PEDESTRIAN WALKWAY NETWORK; (b) RIVER; (c) LAKES; (d) WATER STREAMS; (e) VEGETATION.

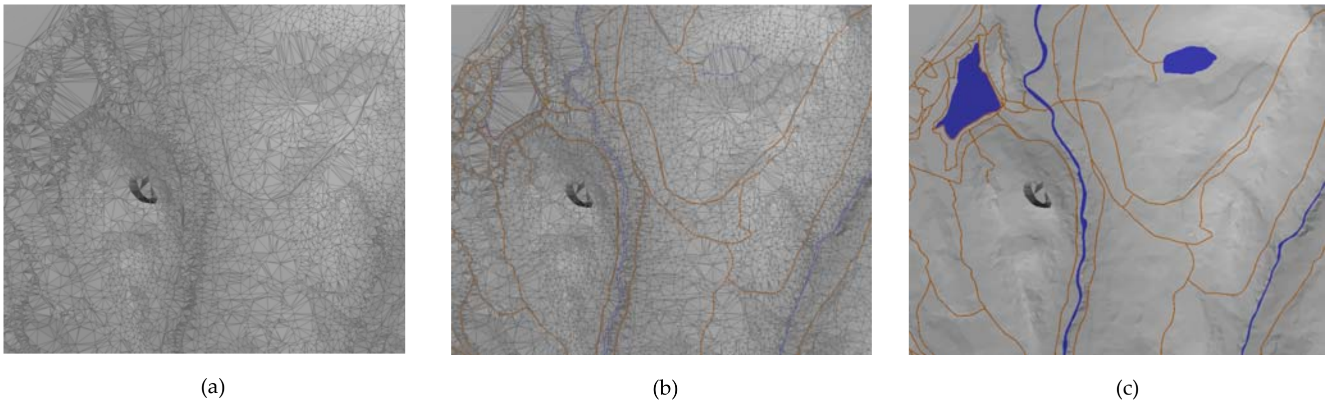


FIG. 11 (a) SPATIAL DESOMPOSITION, (b, c) SEMANTIC MERGING AND MAP FUSION OF MONTMORENCY EXPERIMENTAL FOREST

Secondly, an upper view is proposed with orthogonal projection to represent the GIS data as a standard map. In this view, the user can scroll an zoom the map ((1) in FIG. 9), allowingfor accurate view of any portion of the environment. Additionally, one can select a position in the environment in order to retrieve the corresponding data ((2) in FIG. 9), such as the underlying triangle geometry, the corresponding height, or the associated semantics.

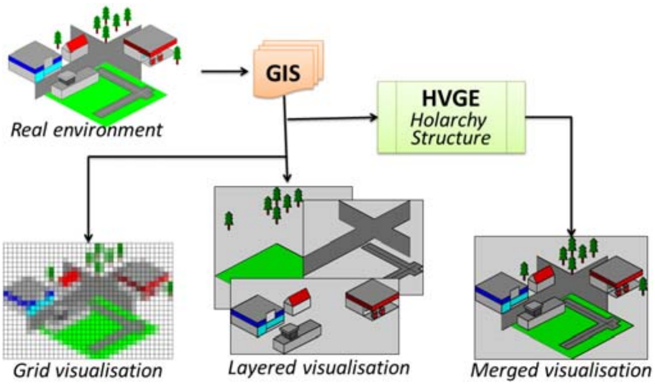


FIG. 12 GIS VISUALISATION APPROACHS. THE PROPOSED HOLONIC IVGE MERGES INFORMATION AND PRESENVES GEOMETRIC ACCURACY

Conclusions

In this paper, a novel holonic approach has been proposed to model large scale geographic environments. This approach extracts an environment holarchy from realistic GIS data and combines the grid-based facility to merge geographic semantic information with the accuracy of vector-based geometric representations. The interest of a holonic view of the environment is that it provides a scalable multilevel model to express complex real world environments.

The holonic approach opens perspectives to represent different levels of detail, from a high-level coarse-grained view of the environment to a low-level fine-grained one. In addition, the suitability of the holonic approach has been shown to organise the data generated by the exact space decomposition into an environment holarchy. The environment holarchy allows us to take advantage of common and efficient graph theory algorithms to examine its structure, and especially graph traversal ones. Interactation with the environment holarchy isto retrieve nodes which correspond to cells, groups of cells, or zones; depending on the holarchy level. Once a node is obtained, it is possible to extract its corresponding data such as the elevation and the semantics information.

Given the above-mentioned characteristics, the environment holarchy opens large perspectives to many spatial reasoning algorithms that can be easily applied, such as path planning or virtual navigation. Actually, we are currently working on an industrial application of the VGE for sensor webs management (Mekni, 2010). Indeed, this informed environment is particularly well suited to such a domain, since it allows efficient path planning, navigation, and deployment algorithms and provides useful spatial data needed for situated sensor agents' behaviours.

Further improvement on the environment description should be made by using topological graph abstractions, which will allow us to reduce the complexity of the graph exploration algorithms, and also to deduce additional properties, such as the reachable areas for a human being with respect to variations of land slopes. Then, new information should be attached to the environment description in order to represent mobile or decorative elements.

These elements could be humans, vehicles, or even street signs, dependent on the objectives of the virtual

reality application. Thanks to the geometrical accuracy of our approach, it will be relatively easy to add this information at any position. Furthermore, these additional localised data may also be of interest for crowd simulation, in order to simply enhance the visual output, but also to take advantage of advanced spatial reasoning.

ACKNOWLEDGEMENT

This research was supported in part by the Grant in Aid (2013-2015) provided by the University of Minnesota. The author would like to thank the reviewers for their valuable comments.

REFERENCES

Chen, S.-G., & Wu, J.-Y. (2005). A geometric interpretation of weighted normal vectors and its improvements., (pp. 422-425).

Farenc, N., Boulic, R., & Thalmann, D. (1999). An Informed Environment dedicated to the simulation of virtual humans in urban context. In P. Brunet, & R. Scopigno (Ed.). *18(3)*, pp. 309-318. The Eurographics Association and Blackwell Publishers.

Fletcher, M., & Hughes, J. (2006). Technology and Policy Challenges to be Met for Introducing Holons into Factory Automation Environments.

Gong, J., & Hui, L. (1999). Virtual Geographical Environments: Concept, Design, and Applications., (pp. 369-375).

Goodchild, M. F. (2006). {GIS} and disasters: Planning for catastrophe. *Computers, Environment and Urban Systems, 30*(3), 227-229.

Kallmann, M., Bieri, H., & Thalmann, D. (2003). Fully Dynamic Constrained Delaunay Triangulations. (G. Brunnett, B. Hamann, & H. Mueller, Eds.) *Geometric Modelling for Scientific Visualization*.

Koestler, A. (1967). *The Ghost in the Machine.*

McGuire, P., Liggins, G., Wojcik, P., Benaskeur, A., & Brennan, R. (2006). The Application of Holonic Control to Tactical Sensor Management. (pp. 225-230). IEEE Computer Society.

Mekni, M. (2010). A Multi-Agent Geo-Simulation Model for Intelligent Sensor Web Spatial Coverage Management Using IVGE. *International Journal of Computers and Communications, 4*(1), 17-30.

Mekni, M. (2011). *Automated Generation of Geometrically-Precise and Semantically-Informed Virtual Geographic Environments Populated with Spatially-Reasoning Agents* (Vol. 1). (Dissertation, Ed.) Dissertation.com.

Mekni, M. (2012). Abstraction of informed virtual geographic environments. *Geo-spatial Information Science, 15*(1), 27-36.

Musse, S. R. (2000). *Human crowd modelling with various levels of behaviour control.* EPFL. EPFL.

Rodriguez, S., Hilaire, V., Galland, S., & Koukam, A. (2006). Holonic Modeling of Environments for Situated Multi-agent Systems. In *Environments for Multi-Agent Systems II* (pp. 18-31).

Tecchia, F., Loscos, C., & Chrysanthou, Y. (2002). Visualizing Crowds in Real-Time. *Computer Graphics Forum, 21*(4), 753-765.

Wang, X. (2005). Integrating {GIS}, simulation models, and visualization in traffic impact analysis. *Computers, Environment and Urban Systems, 29*(4), 471-496.

Weyns, D., Omicini, A., & Odell, J. (2007). Environment, First-Order Abstraction in Multiagent Systems. *Journal of Autonomous Agents and Multiagent Systems, 2006*, 5-30.

Yang, W., Gong, J., Hu, C., & Wang, W. (2006). Collaborative 3D Modeling of Large-Scale Virtual Geographic Environment. *Technologies for E-Learning and Digital Entertainment*, 829-839.

Zhu, J., Gong, J., Lin, H., Li, W., Zhang, J., & Wu, X. (2005). Spatial analysis services in virtual geographic environment based on grid technologies. (J. Gong, Q. Zhu, Y. Liu, & S. Wang, Eds.) *MIPPR 2005: Geospatial Information, Data Mining, and Applications, 6045*(1), 604-615.